

**MINIATURE LOW POWER SUBMILLIMETER-WAVE SPECTROMETER  
FOR REMOTE SENSING IN THE SOLAR SYSTEM**

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**Abstract** - Mass and power for the next generation of NASA's **heterodyne** spectrometers must be greatly reduced to satisfy the constraints of future small-spacecraft missions. Here we present a new receiver concept for remote sensing in the Solar System, with greatly reduced mass, power, and size compared to instruments implemented in current missions. This spectrometer was originally proposed for operation in the vicinity of the 557 GHz emission from the  $\text{H}_2\text{O}$  ground-state transition. With the 557 GHz mixer and associated multiplier chain still under development, we prototype a 220 GHz version of the instrument to verify the receiver concept, and experimentally demonstrated its functionality. A **novel** LO frequency control technique, which eliminates the active thermal control and phased-lock loop systems, is introduced and experimentally verified. The 220 GHz prototype **Schottky-diode** receiver requires less than 4.8 W, and has a mass of less than 1,1 kg - more than a factor of ten reduction in mass and power compared to current instruments. This significant savings, achieved through minimizing the number of receiver components, does not compromise the functionality **necessary** for example, for a surface based Mars atmospheric sounding instrument. For the 557 GHz version, we anticipate that the total mass would be increased by about 300 g over that of

the millimeter wave prototype, due to several additional components, while required power would be reduced by about 1.5 W with the use of MMIC amplifiers.

## INTRODUCTION

The transformation of water from ice to vapor is one of the most powerful forces for change on planets and small **planetary** bodies. [1-2]. One of the strongest transitions of the  $\text{H}_2\text{O}$  molecule, the ground state transition, occurs in the **submillimeter** wavelength region, near 557 GHz. A capable spectrometer operating in the vicinity of this spectral line can be used to address many of the needs of future Solar System exploration missions. For example, on Mars, such an instrument can characterize the nature and the dynamics of the planetary boundary layer by determining pressure, temperature, and **humidity** over diurnal and seasonal cycles, with measurements of thermal spectral line emissions from CO (near 577 GHz) and  $\text{H}_2\text{O}$ . The mass and power typical of current **heterodyne** spectrometers must be greatly reduced to make them viable as candidate.. for future small-spacecraft missions of this type [3]. For instance, the Microwave Limb Sounder currently **flying** on the Upper Atmospheric Research Satellite (with three **heterodyne** radiometers at about 63 GHz, 185 GHz and 203 GHz), has a mass of 283 kg and requires 162 W of DC power [4]. The **Submillimeter** Wave Astronomical **Satellite** (with two **heterodyne** receivers, at about 490 GHz and 555 GHz), to be launched in 1997, has a **total** mass of 92.5 kg, and requires 60.7 W [5]. The Microwave Instrument for the Rosetta Orbiter (with two **heterodyne** receivers at 236 GHz and 562 GHz, and a **full** back-end spectrometer) is anticipated to have a mass of 16.2 kg, and require 61 W [6]. Such instruments are highly capable, but too large to be implemented in small-spacecraft missions such as those for the Mars Surveyor Program [7].

In this paper, we present a new instrument concept for remote sensing in the Solar System, with greatly reduced mass, power, and size compared to the above mentioned instruments. Initially, the significance of remote sensing in **the** Solar System and the experimental approach are briefly outlined. Next, the proposed miniaturization procedure for a 557 GHz receiver is described in **full**. The novel LO frequency control concept and its implementation are then addressed in more detail. With the 557

GHz mixer and associated multiplier chain still under development, we prototype a 220 GHz-version of the instrument. Experimental results for this compact 220 GHz prototype, which demonstrate the feasibility of the novel LO frequency control, are described as well.

## REMOTE SENSING IN THE SOLAR SYSTEM

Millimeter and **submillimeter** wave spectral lines are valuable probes, for example, of the upper atmospheres of planets and cometary comae. Such lines can be completely resolved with a **heterodyne** receiver, yielding unique information on the velocity and abundance of the observed molecules. In the remote sensing of planets from, for example, an orbiter, we learn about the dynamics and chemistry of the atmosphere. Close-up observations of the coma of a comet, for example from a spacecraft traveling with the comet, allow the coma's parent molecules to be observed as they are generated from spots on the surface and accelerate outwards. Detailed observations of the dynamics and evolution of the coma from the neutral molecules that generate it, are of paramount importance in understanding the nature and origin of cometary bodies. The ground state transition of water at **557 GHz** is an extremely strong line that provides a sensitive look at both **planetary** atmospheres and comets. The Microwave Instrument for the Rosetta Orbiter will include a **heterodyne** receiver in the vicinity of this water line to address the nature of cometary nucleus, outgassing, and the development of the coma.

The Martian atmosphere provides a special case for remote sensing. In addition to downlooking observations, there is an opportunity for sounding the atmosphere from a surface-based platform provided by a lander. The instrument we propose would be capable of performing unique investigations of the Martian planetary boundary layer from a Mars Surveyor Lander. In this case, a simple frequency-scanned radiometer looking upwards from the lander is used to obtain simultaneous temperature and humidity **profiles**. The basis for this determination is the optical thickness of both the 557 GHz ground-state water line and the 6-5 rotational transition of CO near 576 GHz. At any given frequency in the wings of either line, the radiometer observes a signal which is approximately proportional to the average temperature of the molecule along the radiometer line of sight (the

instrument observes in the Rayleigh-Jeans region of the **Planck** thermal emission spectrum of the emitting gas). This temperature **average** is strictly determined as **a weighting by an** approximately exponential function of the distance along the line of sight, the characteristic distance of which is controlled by the frequency separation from the line center. **The** CO 576 GHz transition is optically thick at the line center, and CO is approximately uniformly mixed in the lower atmosphere. Hence a spectrum measured through the line maps roughly into the atmospheric temperature profile, or the physical temperature of the altitude. Inversion techniques can be used to determine this profile from the spectral data, and have been thoroughly developed for the strictly analogous case of the **surface-**based sounding of the Earth's atmosphere using the optically thick oxygen band around 60 GHz [8]. At the same time, the spectrum through the H<sub>2</sub>O line can be combined with the temperature profile determination to infer the vertical distribution of water vapor, or the humidity profile. The vertical distribution of temperature and water vapor in the atmosphere, and their variations with time of day and season, will be extremely useful for models of horizontal as well as vertical water transport. Such parameters are fundamental to understanding the nature of the Martian climate and the seasonal cycle of water that partly characterizes it.

## INSTRUMENT CONCEPT

The block diagram of the proposed **submillimeter** wave receiver is shown in Fig. 1. The **heterodyning** is performed by a **subharmonically-pumped** waveguide mixer using **a** planar Schottky barrier diode. The 280 GHz local oscillator (LO) signal is provided by a 140 GHz **InP** GUNN oscillator driving a multiplier. Two RF bands centered at 556.9 GHz (**H<sub>2</sub>O** line) and 576.3 GHz (CO line) are received and downconverted to intermediate frequencies (IF) of 8 GHz and 11.4 GHz respectively, and subsequently detected through 10 MHz bandpass filters. The **GUNN** oscillator frequency is variable within the range of 140.975 - **141.475** GHz, which gives a sufficient IF bandwidth (of about 2 GHz) for each spectral line. **By** tuning the LO frequency within this range, the 10 MHz IF filters can be positioned at any desired frequency within the H<sub>2</sub>O and CO lines. The

availability of low loss filters limits the IF frequency resolution to about  $1:10^3$ . For applications requiring higher resolution than 10 MHz this approach is still feasible, but requires filter development. The same LO chain, mixer, and IF amplifier chain are used for both RF bands. However, two separate detection channels are required, since currently available 140 GHz GUNN oscillators cannot be bias tuned over a wide enough frequency range to detect both the H<sub>2</sub>O and CO lines at the same IF frequency. The microprocessor controls the GUNN bias voltage to step the signals through narrow 10 MHz filters, and also to compensate its frequency for temperature changes.

The goal of this design is to minimize the number of receiver components, and thus reduce mass, required power, and size of the instrument. The tunable narrow band filters eliminate the need for filter banks or a complicated spectrometer backend, and the instrument functions as an extremely simple but effective spectrometer. The price paid is a significant increase in time required to obtain a spectrum of the atmospheric emission, which is entirely acceptable for Mars sounding applications. Subharmonic pumping simplifies the LO chain by cutting its frequency in half and eliminating the need for an additional solid state multiplier and RF diplexing elements. The downconverted signal from the mixer is detected at the first IF so that no further downconversion is necessary, which eliminates the need for additional low frequency LO sources and amplifiers. A novel frequency control technique is also implemented here, which uses bias-tuning of the GUNN oscillator to produce the desired LO frequency over a wide range of temperature, thus eliminating the need for phase-locked loop and active thermal control systems.

### NOVEL LO FREQUENCY CONTROL

The expected temperature variation on the surface of Mars is more than 50 °C. To ensure that the receiver would function properly in such environment, some kind of thermal regulation would usually be required. Here we propose using knowledge of the temperature dependent behavior of the GUNN oscillator to adjust its frequency, instead of keeping its temperature within a small range with an active thermal control system and controlling its frequency with a phase-locked loop system.

Frequency control for the LO is accomplished through a feedback loop, which consists of a temperature sensor mounted on the GUNN oscillator, a microcontroller, and a programmable voltage supply (Fig. 1). The microcontroller calculates the GUNN bias voltage required to produce the desired frequency, based on the temperature dependent bias tuning curves of the GUNN oscillator, and the measured temperature. The feasibility of this scheme was tested with a 110 GHz temperature compensated GUNN oscillator (ZAX ZFFm8/20/109.8/0.3). Initially, this GUNN oscillator was tested in a temperature range of 0 to 50 °C, with about a 2 °C step, and frequency versus voltage behavior was recorded at each temperature. The test set-up for the GUNN oscillator is shown in Fig. 2. An EIP 578B frequency counter was used to measure the GUNN frequency as bias-voltage was swept with an HP6642A programmable power supply. The GUNN bias voltage was checked with an HP 3478A volt meter, and frequency-voltage pairs were recorded with a PC. The GUNN oscillator was placed in a thermal control chamber, and its temperature was continuously monitored, to ensure that data was taken only after equilibrium was reached at each temperature. The measured GUNN oscillator bias-tuning curves (Fig. 3) show that a tuning range of about 500 MHz is available in the temperature range from 0 °C to 50 °C.

Seventh-order polynomial curve fits of GUNN bias voltage versus frequency were produced at each of 22 measured GUNN temperatures. The coefficients for these curve fits are stored as floating point numbers in an 8 by 22 (one temperature + seven polynomial coefficients) matrix in memory on the microcomputer board. Since each value requires only 6 bytes, the memory demand for this table is quite reasonable (slightly over 1 K in the prototype). In an actual flight system, such a table could easily be produced using mask-programmed ROM for long-term reliability. In order to calculate the GUNN bias voltage that will produce a desired frequency, the microcontroller first measures the temperature of the GUNN oscillator, then steps through the coefficient matrix comparing the temperature of each fit with that of the oscillator. A linear interpolation is performed, using two estimated bias voltages calculated with the coefficients for the fits above and below the actual GUNN temperature. The result is a bias setting for the current temperature which is then sent to the DAC producing the bias voltage. This basic cycle requires about 100 mS to complete, which allows several

adjustments each second when other microcomputer tasks are included. This appears to be adequate to adjust for the normal rate of change of the GUNN oscillator. For the prototype, this program was used on a PC for convenience. The operation of the program with a Motorola 68HC 11 family microcomputer was later verified.

Using the experimental set-up from Fig. 2 and the microcontroller computer program, the error in predicted frequency was recorded. The average frequency error is shown in Fig. 4 versus temperature (a) and output frequency (b) for three cases: the GUNN oscillator connected directly to the frequency counter (without an isolator), with an isolator but without desiccant, and with both an isolator and desiccant. Initially, the GUNN oscillator was connected directly to the frequency counter, but it was determined that an isolator was necessary since there was a large (5 -40 MHz) frequency dependent frequency error. After adding an isolator between the GUNN oscillator and the frequency counter, the frequency error decreased (10 -16 MHz), and a very strong temperature dependence was observed, with the error getting smaller as the temperature was increased. This was interpreted as an indication that the presence of water might be a problem, and consequently the GUNN oscillator and isolator were placed in a zip-locked bag filled with desiccant pouches, and left to dry overnight. The next set of measurements, in a "dry" environment (which will be the case for space applications), exhibited a much smaller error, less than 5 MHz at most temperatures, which is completely acceptable for detection with a 10 MHz wide filter. However, to further insure the accuracy of the LO frequency, measurements symmetrically offset from the center of a spectral line will be compared, and the GUNN frequency adjusted if necessary in actual use. This kind of frequency control results in extremely simple circuitry, and requires very little power, only that which is necessary for the operation of the microcontroller.

## EXPERIMENTAL RESULTS

With the 557 GHz mixer and associated multiplier chain still under development, we prototype a 220 GHz version of the instrument with one detection channel to verify the receiver concept. A block

diagram of the 220 GHz radiometer is shown in Fig. 5a, and a picture of the prototype appears in Fig. 5b. The heterodyne receiver uses a subharmonic planar Schottky-diode mixer [9], a GUNN oscillator described in the previous section for the LO, and an IF at 8 GHz with a 10 MHz bandpass filter. Measured mass and power for this receiver are shown in Table I. The prototype receiver has a total mass of less than 1.1 kg (exclusive of telescope) and a DC power requirement of less than 4.8 W, which is more than a factor of ten reduction in mass and power compared to current instruments. Off-the-shelf amplifiers were used in this prototype. The total power is about evenly divided between the IF amplifier chain and the GUNN oscillator. Though the 10 MHz filter takes considerable space (black box in Fig. 5b), its mass is relatively small (220 g) and it does not require any power. All components chosen for this receiver were design to withstand large temperature variations according to the manufacturers specifications. Projected mass and power for a 560 GHz receiver, with MMIC amplifiers, are also shown in Table I. The submillimeter wave multiplier and second detection channel (Fig. 1) would increase the total mass by about 300 g over the millimeter wave prototype, while MMIC amplifiers are expected to reduce the required power by about 1.5 W.

Scanning the LO frequency across a spectral line (varying the GUNN bias voltage from 8.7 to 10.2 V), causes the LO power to vary by about 3 dB (10-20 row). To verify that this will not change the receiver performance and thus distort the detected signal, the receiver noise temperature, conversion loss, and IF impedance were measured as a function of the GUNN bias voltage. It was found that the double-sided noise temperature varied from 2100 K to 2600 K, conversion loss from 9.5 to 10.1 dB, and IF impedance from 88 to 98  $\Omega$ . Such small variations in these parameters are not expected to affect the receiver performance.

The prototype receiver was tested using a laboratory signal source and a spectrum analyzer as a detector. The signal source consisted of a frequency synthesizer (HP 83623A), a source module (HP 83557A, X4 multiplier), and a frequency tripler [10]. To demonstrate LO tunability, a fixed signal was observed at 210.9 GHz with three different LO settings (109.445 GHz, 109.450 GHz and 109.455 GHz) and monitored at the output of the mixer. This is shown in Fig. 6A, where we can see that the detected signal is identical at all three LO frequencies. Since the laboratory source produced a very

narrow signal, less than 1 MHz wide (Fig. 6a), it was **not** possible to observe different parts of the spectral line by sweeping the LO. The functionality of the end-to-end receiver was therefore demonstrated by varying the signal frequency, and adjusting the LO frequency accordingly, to **always** produce an IF signal at 8 GHz. The output of the IF filter for a signal at 210.9 GHz and an LO frequency of 109.450 GHz, is shown in Fig. 6b.

## CONCLUSIONS

We have demonstrated the reduction in mass and power for a functional **heterodyne** receiver system by more than a factor of 10 **over** existing systems, thus creating a powerful tool for future space missions. Such a compact instrument could be used for example, for remote sensing of the Martian atmosphere from a lander to provide atmospheric data fundamental to understanding the nature of the Martian climate. A 220 GHz prototype radiometer with a total mass of less than 1.1 kg, which uses less than 4.8 W of DC power, was designed, assembled, and tested. Miniaturization and power efficiency were achieved through the elimination of several system components, partly through the use of a novel LO frequency control technique which enables the operation of the instrument for a wide range of temperature. Functionality of this receiver was demonstrated using a laboratory signal source. In the 557 **GHz** version, we anticipate that the total mass would be increased by about 300 g over the millimeter wave prototype due to several additional components, while required power would be reduced by about 1.5 W with the use of MMIC amplifiers.

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**FIGURE CAPTIONS**

Fig. 1 **560 GHz** receiver block diagram.

Fig. 2 Test set-up for the **110 GHz** GUNN oscillator.

Fig. 3 Measured **110 GHz** GUNN oscillator bias-tuning curve in the temperature range from 0 °C to 50 °C.

Fig. 4 The average frequency error versus temperature (a) and output frequency (b) for three cases: without an isolator, with an isolator but without desiccant, and with both an isolator and desiccant.

Fig. 5 (a) A **block** diagram of the **220 GHz** radiometer, and (b) a picture of the prototype. The **220 GHz** prototype has a mass of 1.05 kg, a power requirement of **4.8 W**, and dimensions of **30 x 15x 10 cm**.

Fig. 6 The output of the mixer for a fixed signal at **210.9 GHz**, with LO settings of **109.445 GHz**, **109.450 GHz**, and **109.455 GHz**, demonstrating LO tunability, and (b) the output of **the IF filter** for a **signal** at **210.9 GHz**, with LO set at **109.450 GHz**.

Table I Total mass and power measured for the **220 GHz** prototype, and projected for a planned **560 GHz** receiver. MMIC amplifiers are expected to reduce the required power by about 1.5 W.

Fig. 1

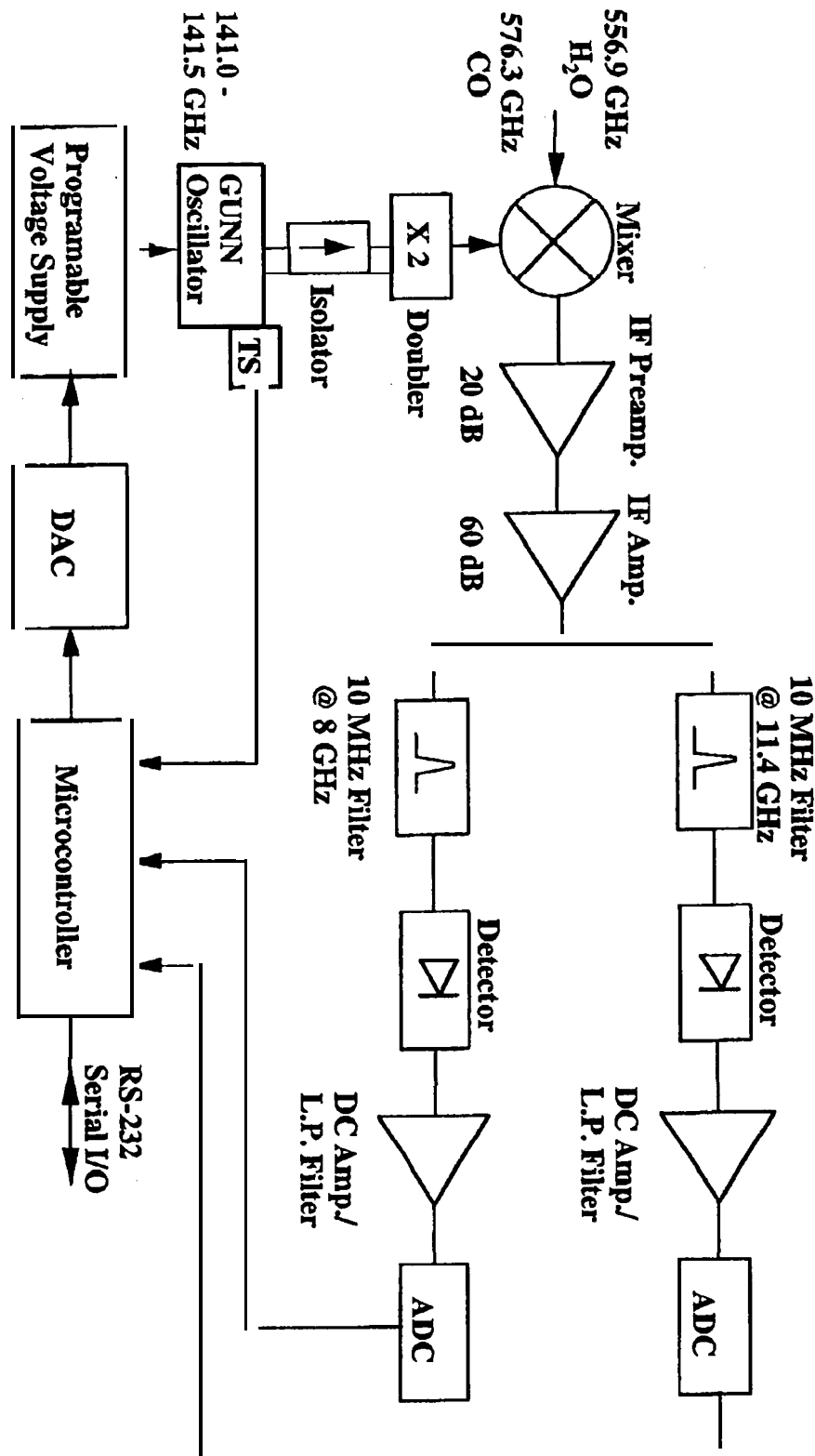


Fig 2

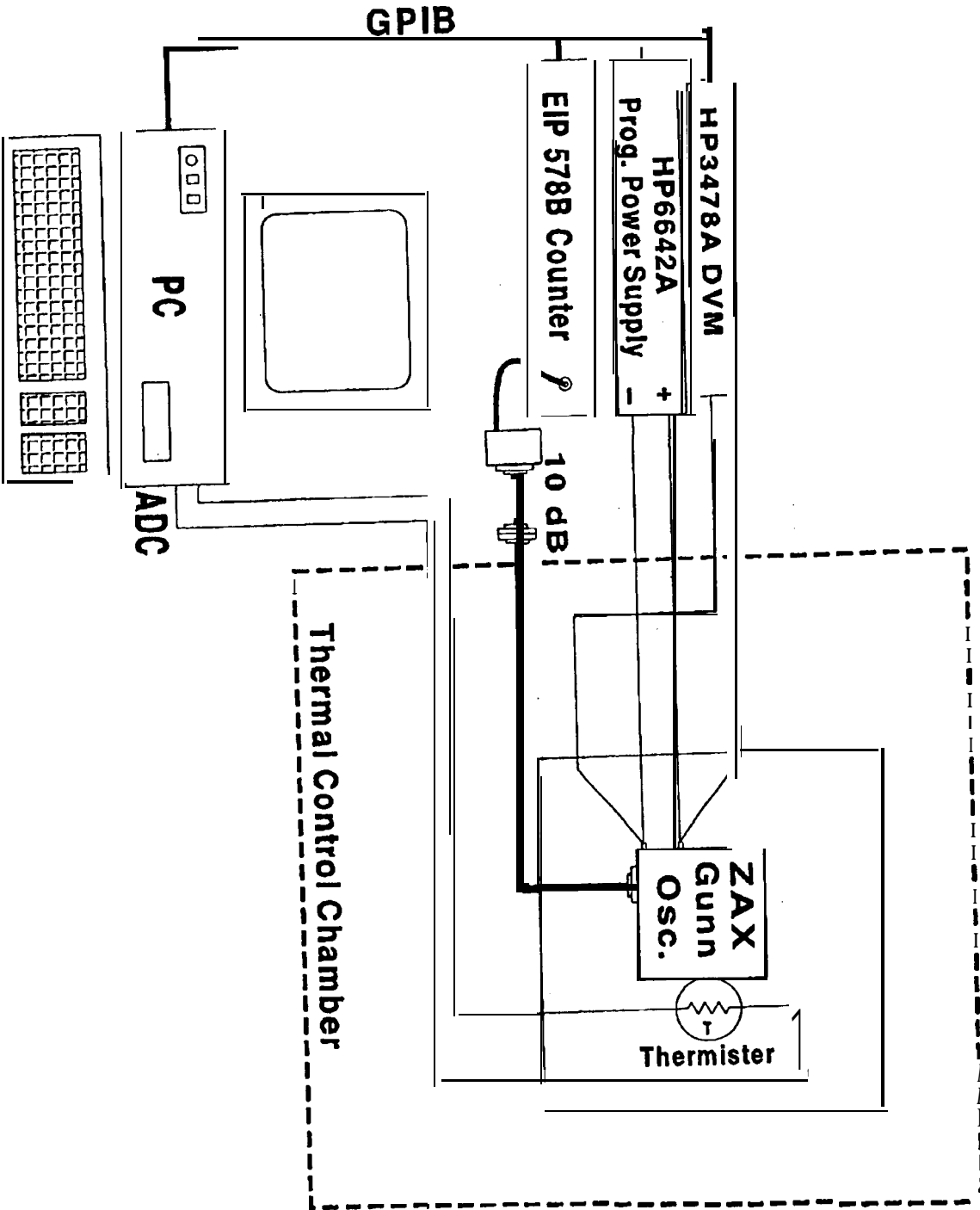


Fig.3

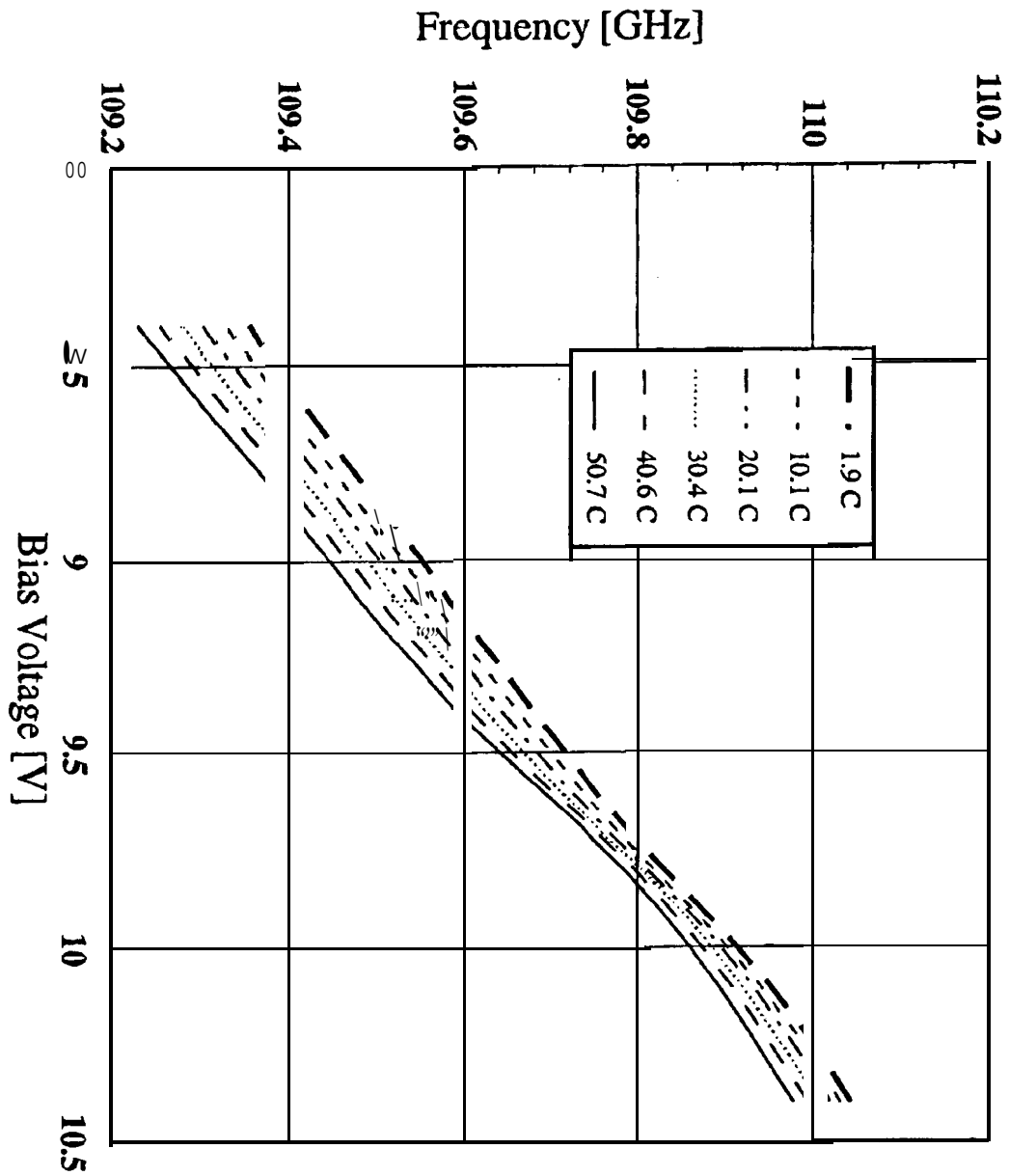


Fig. 4a

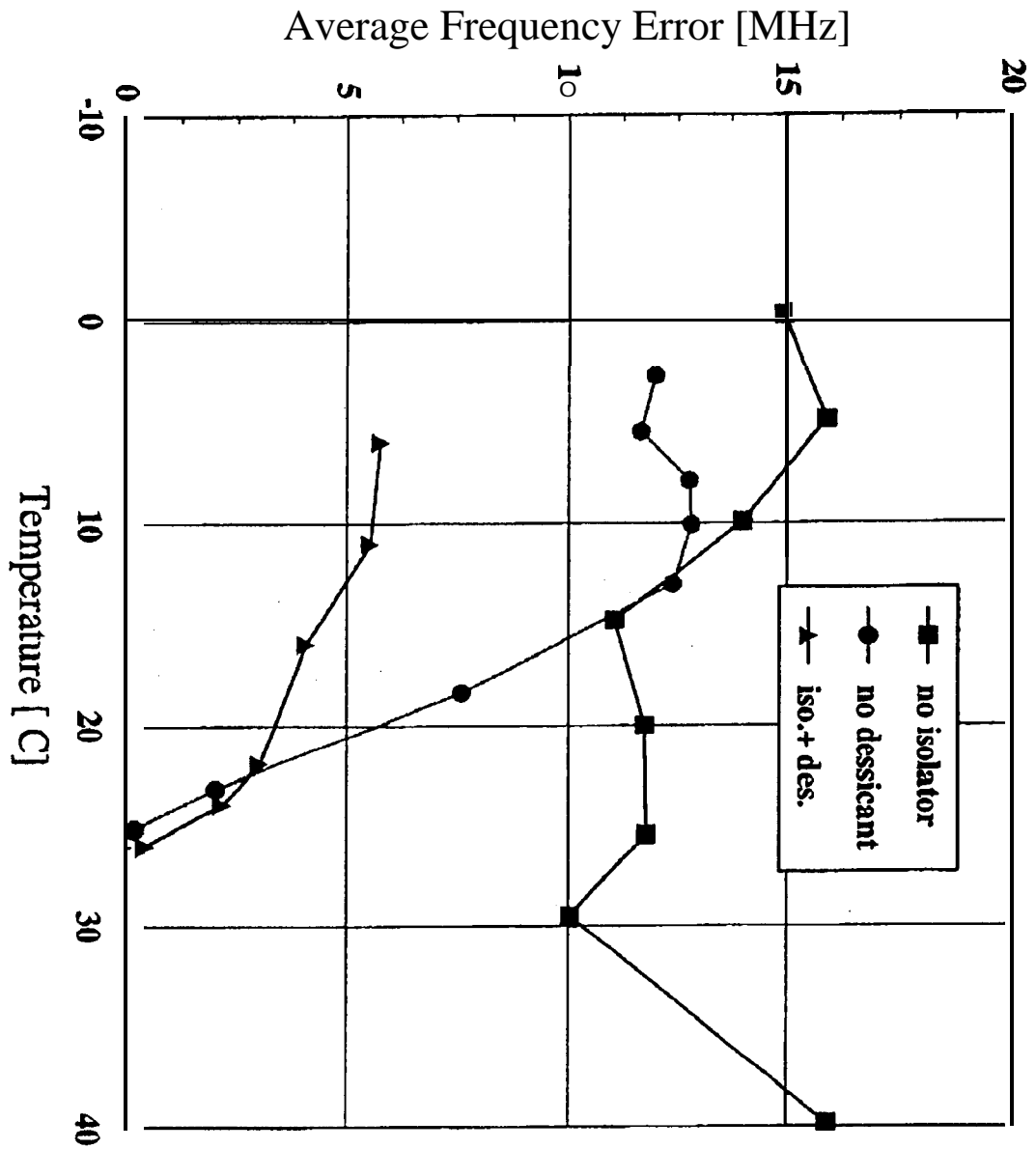


Fig. 4a

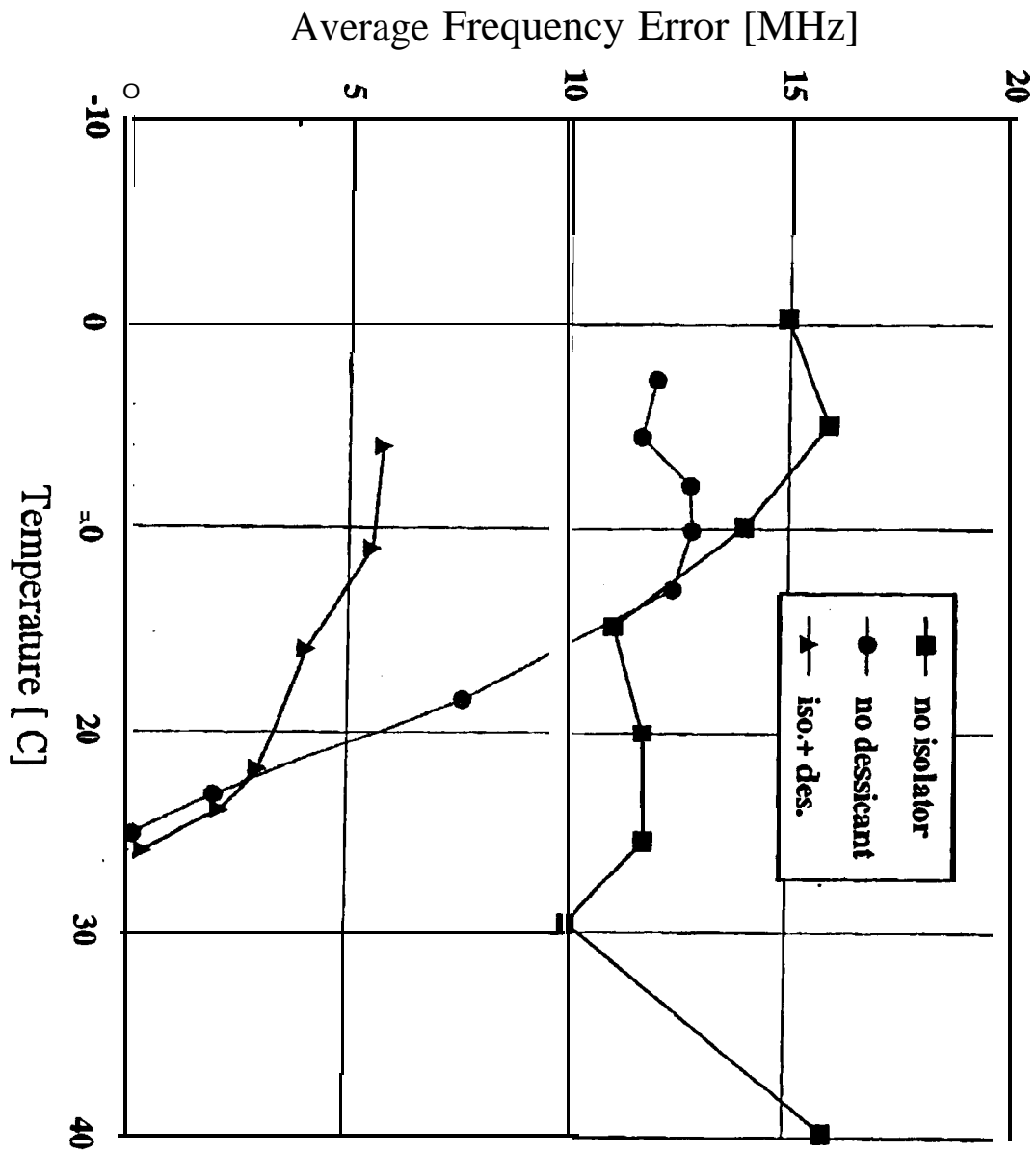


Fig. 4b

